Towards estimating the risk of cascading failure blackouts

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IGERT seminar Northwestern University April 2006
funding from PSerc is gratefully acknowledged
North American power transmission system

• Transmission network >30,000 V, meshed
• Generators, transformers, transmission lines, bulk loads, protection, controls, operators.
• Most of east (or west) of Rockies is connected together and interacting locally and globally.
• Loads and generation change continually; must balance in real time.
• Network size ~ 10,000-100,000 nodes or branches, 100 control centers
power system models

- Assume neglect of fast and slow dynamics
- Nonlinear differential-algebraic equations with hybrid structure and stochastic inputs
- Hybrid structure: control system limits and protection to disconnect components.
- Power flows distribute according to circuit laws and pattern of generation and loads.
- Large number of states and parameters
example of interactions: line trip

- too much power flow heats transmission line
- line expands and sags, flashes over into untrimmed tree
- protection device disconnects line
- transient followed by a steady state redistribution of power flow to parallel paths.
- operators may readjust flows later by changing pattern of generation
- line trips can cascade
blackout interactions

• Typically complicated cascade of various types of failures.
• It can take months to analyze details of the interactions.
• Dependencies stronger when system is heavily loaded.
Figure 6.30. Cascade Sequence

1. 16:05:57
2. 16:05:58
3. 16:09:25
4. 16:10:37
5. 16:10:39
6. 16:10:40
7. 16:10:41
8. 16:10:44
9. 16:10:45
10. 16:13:00
Cascading line failures at start of August 13 2003 blackout

**Figure 5.5. FirstEnergy 345-kV Line Flows**

- Hanna - Juniper
- Star - South Canton
- Sammis - Star
- Harding - Chamberlin

Legend:
- **Hanna - Juniper Line Trip**
- **Star - South Canton Line Trip**
- **Hamins - Star Line Trip**
- **East Lake 5 Trip**
- **Harding - Chamberlin Line Trip**

Time - EDT

MW

Graph showing the time series of MW flows from 12:00 to 16:00 EDT.
Figure 6.17. Measured Power Flows and Frequency Across Regional Interfaces, 16:10:30 to 16:11:00 EDT, with Key Events in the Cascade
Affected Area (4:13 p.m.)

Area affected by blackout
(Service maintained in isolated "islands")

Source: Joint Task Force
Cumulative Line Trips from August 2003 Blackout Final Report

Figure 6.1. Rate of Line and Generator Trips During the Cascade

- Green line: Lines and Transformers
- Red line: Generating Units
- Blue dashed line: GWs of Generation Lost

Graph shows the cumulative number of line/transformers and generators over time from 16:05 to 16:12.

Y-axis: Cumulative Number of Lines/Transformers and Generators
X-axis: Time (16:05 to 16:12)
A bulk systems approach

• Look probabilistically at many blackouts.
• Do not study the gigantic number of possible interactions in detail.
• As in statistical mechanics, look for bulk system events such as phase transitions.
• Try to capture salient and hopefully universal features of cascading failure in simple models.
• Compare with real data.
Blackout risk

- Large, cascading failure blackouts involve huge numbers of dependent, rare and unanticipated events.
- Detailed post-mortem analysis useful (can fix weak points to reduce risk) but does not evaluate overall risk.
- I will first discuss bulk statistical approach to estimate blackout risk using branching process models of cascading failure. This assumes a fixed network with cascading failures.
- I will then, as time permits, discuss complex systems dynamics of grid upgrade.
Blackout risk as size increases

risk = probability \times cost

• Cost increases with blackout size. Example: direct cost proportional to size

• How does blackout probability decrease as size increases? … a crucial consideration for blackout risk!
The power law has huge impact on large blackout risk. 

\[
\text{risk} = \text{probability} \times \text{cost}
\]
NERC blackout data shows power law

- Large blackouts are rare, but have high impact and significant risk
- Conventional risk analysis tools do not apply; new approaches needed
- Consistent with complex system near criticality

NERC = North American Electricity Reliability Council
What is a critical loading?

(1) Kink in mean blackout size

(2) Power law in pdf of blackout size at critical loading

probability $\sim (\text{size})^\alpha$
Summary of OPA blackout model

- Idealized network power flow modeled by linearizing about an equilibrium. Generation to balance load decided by linear programming optimization.
- Only consider probabilistic cascading line outages and overloads with random initial disturbance.
- Blackout size is amount of load disconnected.
IEEE 118 node test network
Fast cascade dynamics

1. Start with viable flows and generation
2. Outage transmission lines with given probability (initial disturbance)
3. Use optimization to redispatch generation
4. Outage lines overloaded in step 3 with given probability
5. If outage goto 3, else stop

Objective: produce load shed and list of lines involved in cascade consistent with system constraints
Critical loading in OPA blackout model

Mean blackout size sharply increases at critical loading; increased risk of cascading failure.
OPA blackout model can match NERC data probability

NERC = North American Electricity Reliability Council

(August 14 2003 blackout is consistent with this power law)
Related cascading failure work

• Cascading in blackout models: Chen & Thorp, Kirschen, Makarov & Hardiman, Talukdar, McCalley, Demarco, Parrilo, Talukdar, McCalley, Demarco, Parrilo, Verghese.

Objectives for quantifying blackout risk

- Monitor risk in simulations of cascading failure
  … only some interactions and events modeled
  … but can evaluate proposed system upgrades
- Monitor risk in real power system
  … no modeling error: rare and unanticipated events and all aspects considered!
- Efficiency matters; need to quantify risk from modest number of blackouts
Branching process model

- Abstract statistical model of cascading (no power systems network)
- Parameter $\lambda$ describes failure propagation
- Parameter $\theta$ describes initial disturbance
- Formula for distribution of total failures:

$$\text{Probability}[r \text{ failures}] = \theta(r\lambda + \theta)^{r-1} e^{-r\lambda - \theta} / r!$$

(saturation omitted from formula)
Branching from one failure

offspring failures (children)

a failure (parent)

number of children \sim \text{Poisson}(\lambda)

mean number of children = \lambda
Branching Process

- each failure independently has random number of children in next stage according to Poisson($\lambda$)

- $\lambda = \text{mean number of children per parent failure}$

- $\lambda$ describes the propagation of failures and proximity to criticality:
  - subcritical case $\lambda < 1$: failures die out
  - critical case $\lambda = 1$: power law distribution of total number of failures
  - supercritical case $\lambda > 1$: failures can proceed to system size
Estimating distribution of number of failures

- Estimate $\lambda$ and initial distribution from failure data
- Then predict distribution of total number of failures from branching process formula
- Closeness of $\lambda$ to 1 gives closeness to criticality.
Estimated propagation:
\[ \hat{\lambda} = \frac{\text{total number of children}}{\text{total number of parents}} = \frac{12}{18} = 0.67 \]

Estimate of initial disturbance:
\[ \hat{\theta} = \text{mean initial failures} = \frac{6}{5} = 1.2 \]

(adjustment for conditioning on nonzero failures not shown)
Initial results comparing empirical pdf from OPA simulation with pdf predicted from same data via estimated $\lambda$ and $\theta$

- pdf is probability distribution of number of line failures
- Test case is IEEE 118 node system
distribution of line failures load factor 0.9

dots = empirical pdf
dashed line = predicted pdf ; \( \hat{\lambda} = 0.2; \hat{\theta}=1.1 \)

probability

IEEE 118 node number of line failures
distribution of line failures load factor 1.0

dots = empirical pdf
dashed line = predicted pdf; $\lambda = 0.4; \theta = 1.5$

probability

IEEE 118 node vs number of line failures
distribution of line failures load factor 1.1
dots = empirical pdf
dashed line = predicted pdf; \( \hat{\lambda} = 0.6; \hat{\theta} = 5.5 \)

probability

190 node

number of line failures
Results suggest that

• Branching process model captures some features of cascading failure.

• Distribution of line failures and propagation of failures $\lambda$ can be efficiently estimated from data. (The efficiency comes from estimating the offspring distribution and then computing the distribution of total failures instead of directly estimating the distribution of total failures, which can have heavy tails.)
Why is North American power grid apparently operated near criticality?

Engineering in response to forces on system:
• Highly optimized tolerance
  (Stubna, Fowler, Carlson, Doyle)
• Self-organization
  (Carreras, Dobson, Newman)
Highly optimized tolerance

- Assumptions: Blackouts spread one-dimensionally and blackout size inversely proportional to engineering resources to limit spread.
- Now minimize expected blackout size subject to finite total engineering resources to represent the effect of system engineering.
- Outcome is pdf of blackout size with asymptotic power tail of slope -1 that can fit NERC data.
Self-Organization; slow complex dynamics of network upgrade

• Network slowly evolves in response to load growth (2% per year) and blackouts.
• Higher loading causes more blackouts.
• More blackouts causes network upgrade and in effect a reduced loading (what matters is loading relative to network capability).
An explanation of power system operating near criticality

Mean blackout size sharply increases at critical loading; increased risk of cascading failure.

Strong economic and engineering forces drive system to near critical loading
OPA model Summary

• Network and cascading failures modeled as before
• underlying load growth + noisy load variations
• engineering responses to blackouts: upgrade lines involved in blackouts; upgrade generation:
  Fix and improve the weakest parts!
OPA model results include:

• self-organization to a dynamic equilibrium
• complicated critical point behaviors
Time evolution

- The system evolves to steady state.
- A measure of the state of the system is the average fractional line loading.

\[ \langle M \rangle = \frac{1}{\text{Number lines}} \sum_{\text{Lines}} \frac{F_{ij}}{F_{ij}^{\text{max}}} \]

\[ F_{ij} \equiv \text{Power flow between nodes } i \text{ and } j \]
OPA model results and North American data

probability

blackout size

Load shed/ Power served

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0

10^{-2} 10^{-1} 10^0

Probability distribution

NERC data

-382-node Network
Robustness of OPA results

• The probability distribution function of blackout size for different networks has a similar functional form - universality?
Effect of risk mitigation methods on probability distribution of failure size

“obvious” methods can have counterintuitive effects in complex systems
Blackout mitigation example

• Require a certain minimum number of transmission lines to overload before any line outages can occur.
A minimum number of line overloads before any line outages

- With no mitigation, there are blackouts with line outages ranging from zero up to 20.
- When we suppress outages unless there are \( n > n_{\text{max}} \) overloaded lines, there is an increase in the number of large blackouts and a decrease in smaller blackouts.
- Overall risk could be worse.
Big picture for blackout risk

- Frame problem as managing risk of blackouts of all sizes (not just the small and most easily analyzed sequences).
- Manage cascading failure by limiting cascades starting but also limiting propagation of failures ($\lambda$).
- Grapple with design and operational tradeoffs between maximizing transfers and blackout risk.
- It is better not to estimate overall blackout risk by guessing or waiting for lots of blackouts to happen. We are suggesting approaches towards estimating this risk.
Research goals

• Seek to confirm universal features in cascading models with varying detail
• Monitor propagation of failures to estimate proximity to criticality, blackout pdf and overall blackout risk
• Better modeling of forces controlling network upgrade.
Broader (and speculative!) themes

• Cascading failure can generally produce large events and heavy tails.
• Bulk systems approach to risk analysis can complement detailed analysis of failures.
• Network evolution is important. Engineered systems are designed and operated in response to strong environmental forces. Modeling these feedbacks and complex systems dynamics can yield important features of the system. Modeling interactions with the environment is challenging!
For more information see papers on web at dobson home page:
http://eceserv0.ece.wisc.edu/~dobson/home.html

[EXTRA SLIDES FOLLOW]
Processing summary data from WSCC July 1996

Line trip times

Log cumulative failures

![](image)

\[ \lambda = \text{line slope} = 1.4 \]
Effect of Loading

- **VERY LOW LOAD**
  - failures independent
  - exponential tails

- **CRITICAL LOAD**
  - power law

- **VERY HIGH LOAD**
  - total blackout likely

log log plots

probability

blackout size
Forest fire mitigation simulation

red = efficient fire fighting
blue = no fire fighting

Number of fires of given size (proportional to probability)

Size of fire
An analogy from statistical physics:

Ingredients of Self-Organized Criticality in idealized cellular automaton sandpile

- system state = local max gradients
- event = sand topples (cascade of events is an avalanche)
  1. addition of sand builds up sandpile
  2. gravity pulls down sandpile
- Hence dynamic equilibrium with avalanches of all sizes and pdf of avalanche sizes with power tail.
<table>
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<th>Sand pile</th>
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<td>loading pattern</td>
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<td>response to blackout</td>
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<td>event</td>
<td>limit flow or trip</td>
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</table>

Analogy between power system and sand pile
how branching processes work
Assume one initial failure for simplicity

The offspring distribution \( Z \) is given by \( P[k \text{ failures}] \) and its generating function is
\[
g(s) = \sum P[k \text{ failures}]s^k
\]

Sum of \( k \) independent copies of \( Z \) has generating function \((g(s))^k\).
Sum of \( N \) independent copies of \( Z \) has generating function
\[
h(g(s)) = \sum (g(s))^k P[N=k]
\]
where the generating function of \( N \) is \( h(s) \).
Generating functions:

\[ g(g(g(s))) \]
\[ g(g(s)) \]
\[ g(s) \]

\[ G(s) = \text{generating function of total failures} \]

\[ G(s) \text{ can be computed from } s \ g(G(s)) = G(s) \]

Key point:
If you can estimate offspring distribution, then you can compute the distribution of total failures.